The Nature of Surface Tilt Along 85 km of the San Andreas Fault – Preliminary Results from a 14-Instrument Array

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Summary – The continuous monitoring of surface deformation near active faults is clearly necessary for an understanding of elastic strain accumulation and elastic and anelastic strain release associated with earthquakes. Fourteen 2-component tiltmeters have been installed in shallow boreholes along 85 km of the currently most active section of the San Andreas fault in the western United States. These instruments operate at a sensitivity of 10^{-8} radians. Five of these tiltmeters, extending along one 35 km section of the fault, have been in operation since June 1973. The results indicate that regional tectonic tilting has occurred before more than ten individual earthquakes or groups of earthquakes with epicenters within ten earthquake source dimensions of one or more instruments. This tilting has a time scale of up to a month depending on earthquake magnitude. The amplitude of these tilts exceeds by almost an order of magnitude that expected from a dislocation model of the source using seismically determined parameters. No indication of rapid or accelerated tilt just prior to these earthquakes has been seen.

I. Introduction

The accepted explanation of the earthquake mechanism, proposed by Reid [15], is the rapid release of slowly accumulated elastic strain energy by fault slip or breakage; however, the details of stress accumulation in the earth's crust are not well understood. This simple explanation, however, is unlikely to be useful in the problem of earthquake prediction where visco-elastic behavior could dominate in the period immediately before an earthquake. In particular, this includes the expected and observed variability of material properties and behavior, both in time (Dieterich [3], Griggs et al. [4] Orowan [12], Scholz [19]) and space. The time scale of seismic stress change will probably also be nonlinear (Stacey [20]).

Precise determination of surface displacement and displacement gradients near active faults may contribute to understanding the earthquake mechanism. Unfortunately, observations of this type are difficult to make and are easily contaminated by instrumental, meteorological, and site effects. Progress in the last ten years has been slow. To obtain useful data, it is still necessary to test the instrument thoroughly under simulated site conditions before installation, to obtain simultaneous meteorologic records, and to place strict checks on the data produced to ensure authenticity, e.g., simultaneous recording on at least two independent instruments.

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By far the easiest method for monitoring surface deformation is to record the associated surface tilt. The best evidence of tilts accompanying earthquakes have come from several observers in Japan (HAGAWARI and RIKITAKE [5], SASSA and NISHIMURA [17]), though some observations of possible anomalous tilting preceding earthquakes have been made in the USSR (OSTROVSKII [13]), Italy (CALOI [2]), and the USA (Wood and Allen [24]). There does not appear from the reported data to be any systematic tilt behavior associated with earthquakes.

To examine the relationship of crustal tilts and earthquakes, the installation of a network of 2-component shallow borehole tiltmeters was initiated in 1973. This network extends along an 85 km section of the San Andreas fault from Mt. Madonna (23°01′N, 121°42′W) to Dry Lake (36°29′N, 121°05′W). This is currently the most seismically active section of the fault. Fourteen instruments have now been installed and five have been in operation since June 1973. The purpose of this paper is to present the records from several of these instruments and discuss some possible relation to earthquake tectonics.

2. The instruments and their installation

Although observations of crustal tilting data back to the early 1900's (OMORI [11]), the basic problems plaguing this kind of measurement are not easy to minimize. The most important of these are:

1) meteorological loading effects,
2) thermal and mechanical instabilities both in the instrument and the site,
3) the heterogeneous nature of crustal rock and surface strain fields.

Deep mine installations may reduce some surface noise problems but introduce others such as tunnel-shape effects, as discussed by KING [8], complex fracturing due to mining, and cost. Few deep mines exist in seismically active areas. If reliable data on tilt before earthquakes are to be obtained, it appears necessary to successfully operate near-surface installations at as many closely spaced sites as possible.

The instrument used in this array is the model 541B manufactured by the Autonetics Division of Rockwell International. It consists of a bubble in a conducting electrolyte contained under a concave quartz lens. The position of the bubble is sensed by two A.C. bridge circuits which have a common electrode at the bottom of the fluid cavity and orthogonal pairs of sensing electrodes deposited on the lens surface (KOHLENBERGER et al. [10]).

Prior to installation the calibration, linearity, thermal, and mechanical stability were measured by JOHNSTON [6]. The most important of these parameters is the mechanical stability, which in the worst case was 2×10^{-7} radians in a two-month period. This measurement was made by suspending the instrument, with viscous damping, on a long, thin stainless steel wire. The output depends then only on the gravitational

constant and the mechanical and electronic stability. With the viscous damping removed, this was also a convenient way to measure impulse response.

Sensitivity to temperature was high (5×10^{-8}/°C near the null balance position). The range of temperature at 3 m depth is not expected or observed to exceed a few degrees and operation is kept near the null balance position. Sensitivity to thermal gradients was also high; however, in the borehole installations used, thermal gradients have been minimized (<0.001°C/cm).

The installation consists of a pit 1 m in diameter and 2 m deep, lined with a fiberglass culvert surrounded by a layer of tar and gravel to prevent surface runoff from seeping down the outside and underneath the culvert. Extending down about 2 m from the bottom of the pit is a 15 cm diameter borehole lined with aged steel tubing, closed at the bottom. The sensor is wellpacked with fine grain silica sand near the bottom of the borehole. The closely packed sand appears to have better stability than the surrounding fault zone materials. We are currently testing a more rigid mount using an expansive grout to cement the sensor in the borehole. The tiltmeter electronics are located in the bottom of the pit, which is filled with marble-sized styrofoam pellets. Battery power and recording facilities are remotely located in a second pit. This method of installation is similar to that described by ALLEN et al. [1].

As a check on the whole system, two installations, 20 m apart, were completed at one site. For various reasons, the site selected for this test has proven to be a bad choice. However, the two instruments have tracked one another since installation within 0.8 microradians prior to the rainy season. As an additional check on the system, surveyed level lines have been established across or near the instrument sites and will be resurveyed periodically. Preliminary results of the first resurvey at the Bear Valley site show close agreement in direction and magnitude with recorded instrumental tilt (KINOSHITA [9]).

Site selection was found to be a crucial factor in the shallow borehole installation. Figure 1 shows the sites selected and the tiltmeters that have been installed. The instruments are located between 1 and 4 km from the fault with a spacing of about 6 km on alternate sides along the fault. The Nutting and Libby instruments, the two instruments at the Sage Range (North and South), and an instrument near Tres Pinos which has given records of varying quality due to installation and recording problems, were installed in June 1973. The Aromas and San Juan Bautista sites have been operational since December 1973, and the Stone Canyon and Bear Valley instruments were installed in January 1974. Other instruments have been installed more recently.

Sites selected on the basis of radial symmetry, homogeneity of material, and remoteness from topographical changes show no apparent diurnal temperature effects or ground loading effects due to rainfull at a sensitivity of 10^{-7} radians. It was not always possible to satisfy these criteria. The primary tilt effects observed at installations near steep topography were thermoelastic in origin. Meteorological effects also were more obvious at these sites.
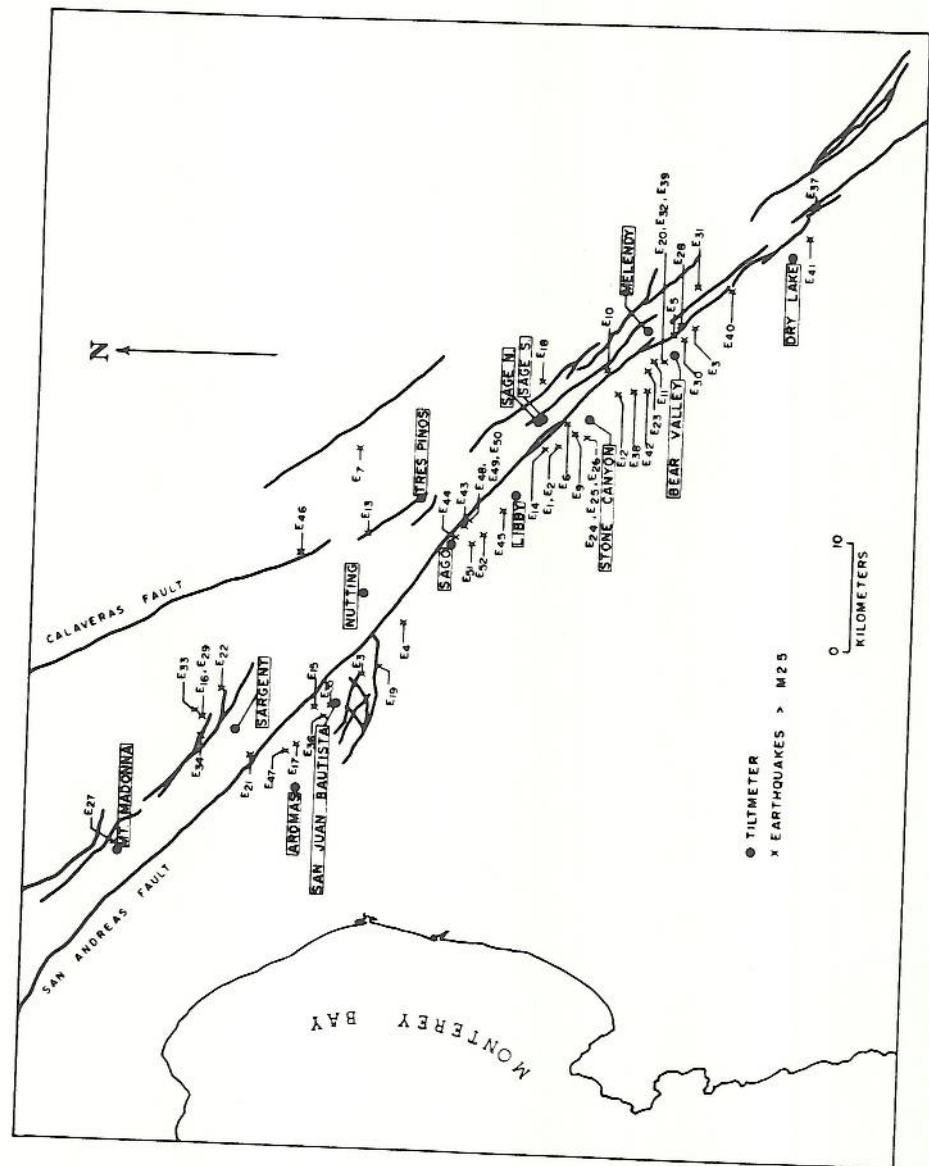
Figure 1

Tiltmeter sites (circles) along an 85 km section of the San Andreas fault from Dry Lake (36°29'N, 121°05'W) to Mt. Madonna (37°01'N, 121°42'W), and earthquakes (×'s) of $M > 2.5$, listed in Table 1, which have occurred near the instrument sites

3. The earthquake source region

Various models of the earthquake source region imply particular, though sometimes highly complex, spatial distributions of surface tilting prior to and following earthquakes. The possibility of large-scale dilatant behavior in the crust associated with earthquakes, which has been suggested by SCHOLZ et al. [19] to explain most precursive phenomena, implies, in its simplest form, symmetric uplift. The detection of this uplift should be possible with a sensitive tiltmeter array. In contrast, a slip model of the earthquake source region implies an asymmetric tilt field. In particular, this is the case for strike-slip and thrust faulting. Using a simple dislocation model in an elastic homogeneous half-space to represent fault slip, Press [14] calculated the tilt field at distances large compared to the earthquake source dimension. More recently, ROSENMAN and SINGH [16] have calculated the surface tilt fields for several elastic and viscoelastic models. These fields are highly dependent on viscosity and other model parameters. In terms of such slip models, tiltmeters operating at tidal sensitivity should resolve tilts as distant as 8.5 source dimensions from the epicentral region or about 30 km for a magnitude 4.0 earthquake. Source dimension (L) as a function of magnitude (M_L) for San Andreas earthquakes has been plotted by THATCHER and HANKS [22] and appears to best fit a relation (WYSS and BRUNE [25]) which can be approximated by

$$M_L = 1.9 \log L + 2.9. \tag{1}$$

With the instrument separation selected, therefore, some indication of regional deformation around the fault is expected with the tiltmeter array. Far-field and perhaps also near-field tilt effects from earthquakes with magnitudes greater than 4 should be observed on at least one instrument.

A crude but convenient way of ranking the effects of various earthquakes was to consider a weighting function, W, dependent on source dimension (L), depth (D), and distance (Δ):

$$W = K \frac{LD}{\Delta} \tag{2}$$

where K is a constant. This function probably will overestimate the effects of distant earthquakes due to the assumption of linear fall-off with distance. For central California earthquakes the observed range of depths is limited to between 2 and 10 km.

After carefully examining the tilt records at the times of small to moderate earthquakes in central California, very few cases of anomalous tilt behavior were observed for earthquakes that occurred at distances greater than 10 L. Preliminary data analysis has been concentrated, therefore, on earthquakes with less than a 10L distance to an instrument.

4. Summary of tilt observations

The general character of the raw data tends to show a long-term systematic tilt which can be as much as 2×10^{-6} radians per month, depending on the site, on which

Table 1

Occurrence times, locations, and magnitudes (>2.5) of the local earthquakes E_1 to E_{52} that have occurred since June 1973 in central California near the tiltmeter installations

No.	Date	GMT	Lat. N.	Long. W	Depth	Mag.
E_1	July 5	1147	36 39.2	121 18.2	4.8	2.7
E_2	July 5	1702	36 39.2	121 18.1	5.5	3.0
E_3	July 9	2100	36 48.7	121 32.9	6.2	3.3
E_4	August 7	0417	36 46.8	121 29.3	5.0	3.0
E_5	September 17	0531	36 33.6	121 11.4	4.8	2.8
E_6	October 4	0537	36 38.8	121 17.6	6.7	2.9
E_7	October 6	0918	36 49.0	121 18.4	8.3	2.7
E_8	October 12	1919	36 32.5	121 10.5	7.6	2.8
E_9	October 14	1657	36 38.6	121 17.8	5.2	2.5
E_{10}	October 27	2008	36 36.9	121 13.6	2.43	2.9
E_{11}	November 15	0948	36 34.7	121 12.9	6.2	2.8
E_{12}	November 24	0108	36 36.6	121 15.0	5.8	2.8
E_{13}	December 13	0217	36 48.6	121 24.0	7.7	2.7
E_{14}	December 14	1204	36 39.9	121 18.5	9.0	2.6
E_{15}	December 14	2356	36 50.6	121 35.3	6.0	2.9
E_{16}	January 10	1122	36 57.1	121 35.8	7.7	4.3
E_{17}	January 23	1556	36 52.2	121 37.3	6.0	3.0
E_{18}	January 27	1922	36 35.2	121 14.0	6.8	2.7
E_{19}	February 1	0327	36 47.6	121 32.6	8.5	3.6
E_{20}	February 7	1035	36 34.2	121 12.8	5.0	3.2
E_{21}	February 8	0004	36 54.5	121 37.7	1.5	2.7
E_{22}	February 8	0215	36 56.2	121 33.3	4.8	2.7
E_{23}	February 20	1055	36 35.3	121 13.7	12.8	2.8
E_{24}	March 8	1855	36 38.3	121 17.6	4.0	2.8
E_{25}	March 8	1856	36 38.6	121 17.5	4.1	2.9
E_{26}	March 8	1910	36 38.3	121 17.2	4.2	3.1
E_{27}	March 16	1624	37 1.1	121 43.6	9.7	3.0
E_{28}	March 17	0029	36 33.5	121 10.6	3.5	2.5
E_{29}	March 31	2306	36 57.2	121 35.8	5.1	3.4
E_{30}	April 7	1047	36 33.1	121 11.4	3.7	3.0
E_{31}	April 7	2207	36 32.6	121 8.1	9.1	2.8
E_{32}	April 9	1637	36 34.5	121 12.9	5.0	2.8
E_{33}	April 10	1713	36 56.9	121 35.7	4.7	2.5
E_{34}	April 17	1930	36 57.1	121 36.0	5.0	3.3
E_{35}	April 22	0821	36 50.5	121 34.4	5.0	2.7
E_{36}	April 22	0824	36 50.5	121 34.9	5.8	3.0
E_{37}	April 25	0440	36 27.0	121 3.3	8.9	3.0
E_{38}	April 25	1905	36 35.5	121 14.6	9.6	2.5
E_{39}	April 30	0545	36 34.4	121 12.8	5.3	2.8
E_{40}	May 4	0347	36 30.9	121 8.0	11.0	3.1
E_{41}	May 5	2013	36 27.2	121 5.1	3.3	2.6
E_{42}	June 10	0003	36 35.0	121 14.5	8.1	2.8
E_{43}	June 12	1850	36 44.0	121 23.1	6.8	2.9
E_{44}	June 12	1921	36 44.1	121 23.6	7.3	3.3
E_{45}	June 12	1922	36 42.0	121 22.5	7.1	3.3
E_{46}	June 14	0249	36 52.2	121 25.0	5.7	3.1
E_{47}	June 15	1410	36 52.7	121 37.7	6.2	2.6
E_{48}	June 15	1749	36 43.9	121 23.7	6.9	3.3

Table 1—*continued*

No.	Date	GMT	Lat. N.	Long. W	Depth	Mag.
E_{49}	June 15	1816	36 43.9	121 24.0	6.4	2.5
E_{50}	June 15	1818	36 43.6	121 23.9	7.4	2.7
E_{51}	June 15	1900	36 43.3	121 24.1	5.5	2.8
E_{52}	June 15	1929	36 43.5	121 23.9	6.6	2.9

are superimposed shorter-term perturbations with time spans of weeks to a month. Some very short-term tilt changes (minutes to hours) have also been observed.
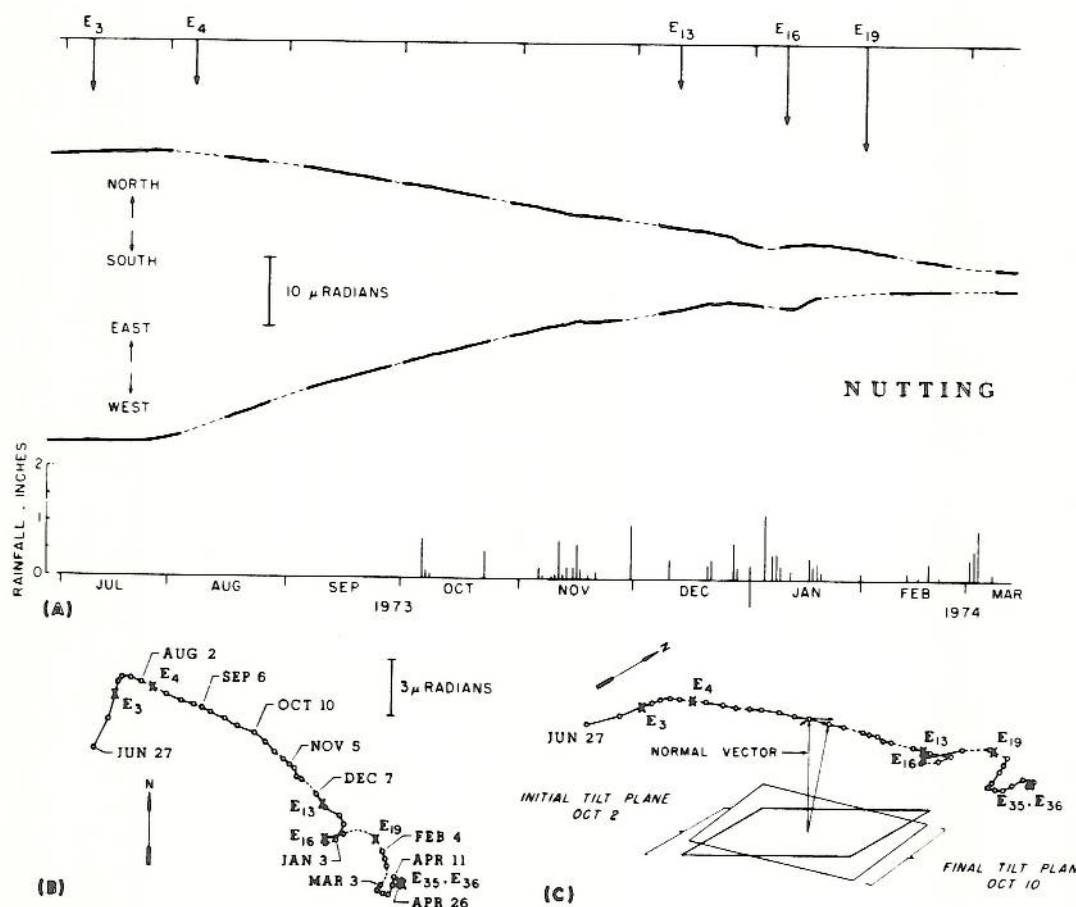
Figure 2
a) Time compressed raw record, with rezeros removed, from the Nutting Ranch site. The occurrence times of earthquakes are noted by arrows having length proportional to *W*. b) Cumulative plot of weekly average tilt-change vectors for the Nutting site. c) The tilt-change vector related to the tilt-plane

Many earthquakes having magnitudes M_L in the range $2.5 < M_L < 4.3$ have occurred in the area of installation since the array has been in operation. The inter-mediate-term tilt perturbations of up to a month appear to be associated with these earthquakes. In this paper the emphasis will be on these effects, which are best illustrated by filtering the data to remove frequencies of greater than one cycle/day. This averaging removes the diurnal and semi-diurnal solid-earth tidal perturbations and, in some cases, a diurnal thermoelastic effect. It is important to point out that no indication has yet been found of any accelerating tilt immediately before (hours to seconds) any of the 52 earthquakes that have occurred within 25 km of an instrument since the array has been operating.

A typical example of the raw data from the Nutting site is illustrated in Fig. 2a. Here the north–south and east–west components are shown with electrical offsets removed. Tilt vectors generated from these data were monitored with time at each instrument. The change in tilt behavior from week to week can be displayed by plotting a weekly average tilt-change vector, as shown in Fig. 2b, where each vector represents the amount and direction of tilting during a given week. The physical meaning of such a plot is illustrated in Fig. 2c. The amplitude and azimuth of running weekly average tilt-change vectors are plotted in Fig. 3 for the six instruments that have been longest in operation.

The earthquakes that have occurred within a 10-source dimension distance from an instrument are listed in Table 1 and are plotted, together with the site locations, in Fig. 1. Their occurrence is noted in Fig. 3 by arrows. The length of the arrows repre-senting these earthquakes is proportional to the weighting function W.

Temperature and rainfall records have also been included in Fig. 3. It was not expec-ted that temperature changes could explain the observations. However, since the instru-ments do have a thermal response, the possibility of some thermal contamination is real. At the installation depth, the diurnal temperature range is less than $0.1°C$ and the annual range is less than a few degrees. No obvious temperature effect has been found.

Careful examination shows some correlation between tilt and rainfall, particularly at sites lacking symmetric topography. However, some of the dramatic changes in the tilt vector appear to be independent of rainfall and in each case there are some periods of rainfall not accompanied by significant changes in tilt. There does appear to be some relation between earthquakes and surface tilt. Curiously, it is the direction of the tilt-change vector that appears most unambiguously related to subsequent earthquake occurrence. This can be emphasized, as in Fig. 4, by differentiating the azimuth plot. Weighted earthquakes and their occurrence times, together with rainfall and tempera-ture records, are also included. This plot is useful for identification of general anomalous periods and coherency between independent instruments, as between Nutting and Libby during January 1974. The peaks have, of course, little physical significance.

The amplitude information included in Fig. 3 is complicated. Details of the tilt amplitude behavior and the relation this has to the earthquake source mechanism are currently being investigated.
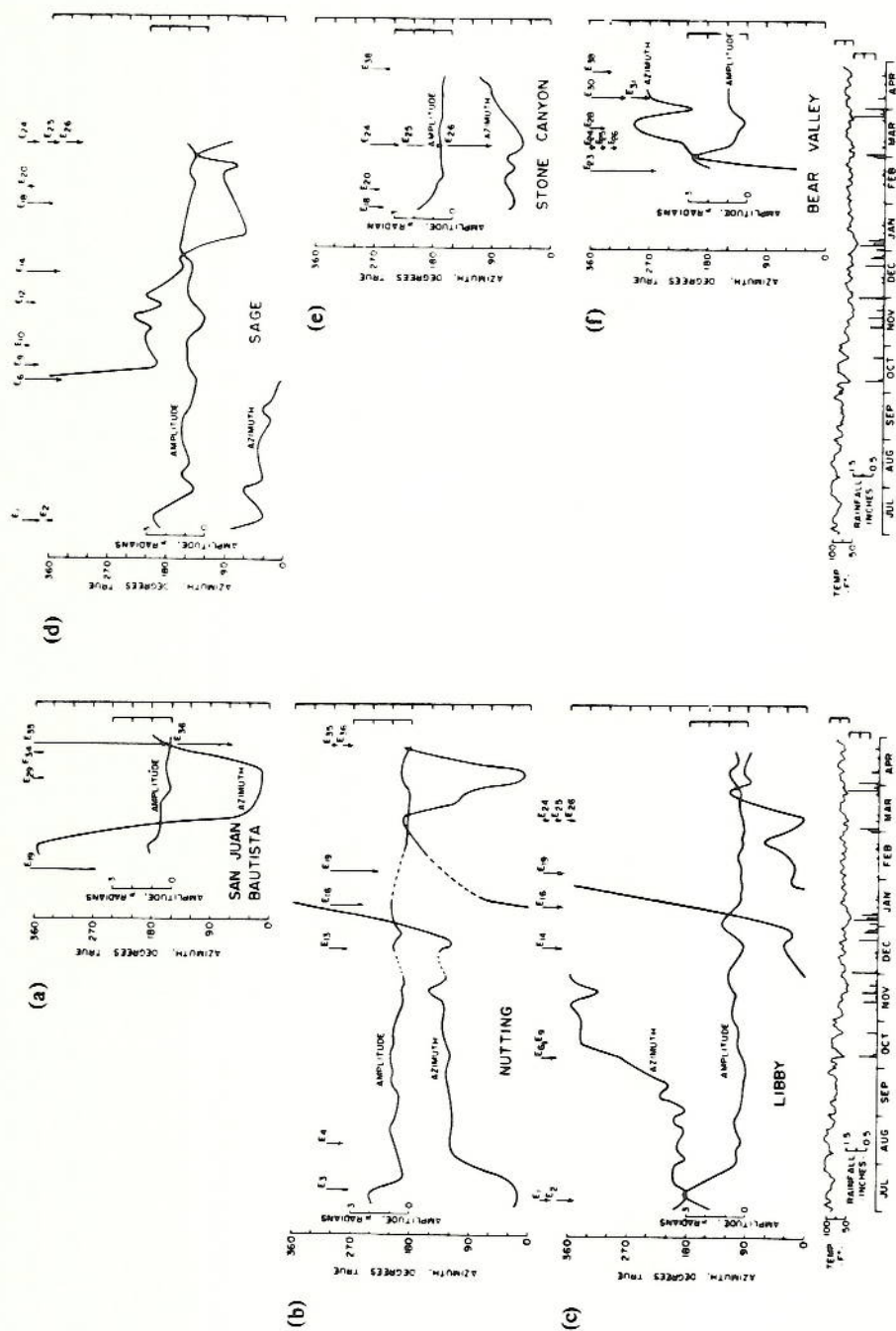
Figure 3a–f

Azimuth and amplitude of the weekly average tilt-change vectors for the six tiltmeter sites longest in operation. Temperature and rainfall are included along the abscissa
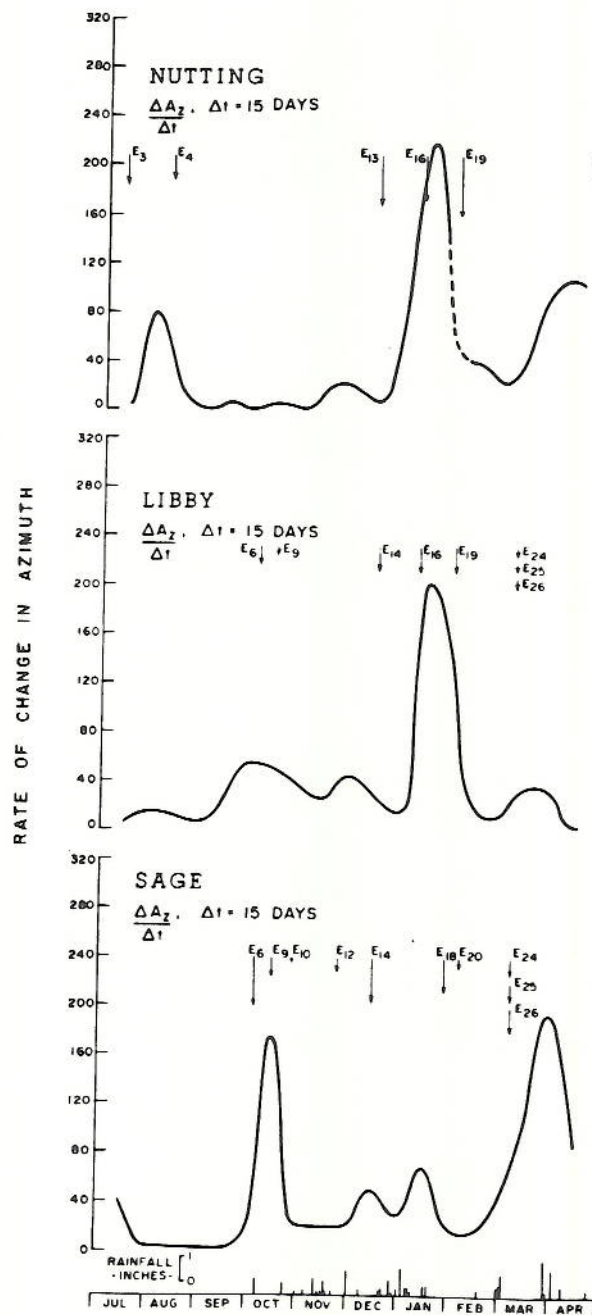
Figure 4
Differentiated average tilt-change vector azimuth records for the Nutting, Libby, and Sage sites

In Fig. 3 a significant slow rotation of the resultant weekly tilt-change vector (azimuth) at the Nutting site can be seen, beginning on about 17 December. On 10 January, a magnitude 4.3 earthquake (E_{16}) occurred 17 km, or roughly four source dimensions, north-west of the Nutting Ranch site, at a depth of 7.7 km, some 24 days after the onset of anomalous tilt behavior. This behavior is also apparent in Fig. 2. On 1 February, earthquake E_{19} ($M_L = 3.6$) occurred 7.4 km west of the Nutting site, or roughly 3.7 source dimensions distant. These earthquakes appear also to have affected the Libby Ranch site, at distances of nearly 8 and 10 source dimensions respectively. Other incidences of this type of precursory behavior can be seen in Fig. 3, but they are not as large as the above events and precursor times are correspondingly shorter. The range of magnitudes of the earthquakes that have occurred so far is too small to test fully the idea of WHITCOMB et al. [23] that the relation between magnitude (M) and presursor time (t) takes the form

$$\log t = 0.8M - 1.9 \qquad (3)$$

although the data do not violate the equation.

An important aspect of the data is the long term or secular tilting which takes place at each site and which can amount to several microradians per month, depending on the site and, in some cases, time. This secular trend has been consistent at a site such as Nutting, while at other locations, such as the Sage site, the trend has changed direction markedly. In general, the secular trend increases with seismic activity in the surrounding region.

Preliminary results indicate that if the secular trends are removed from the data, then the resultant tilt vectors prior to and following earthquakes do not systematically point away from the earthquake as would be expected for the simplest dilatancy model. Rather, the observed vector amplitude and direction are dependent on where the earthquake occurs with respect to the instrument. This position dependence would be expected for slip models of the earthquake source. However, the amplitudes are larger by almost an order of magnitude than those expected from a dislocation model of the earthquake source using seismically determined source parameters.

Because of its amplitude it is unlikely that the secular trend is of instrumental origin. Since all installations are identical, and since all sites are picked for apparent stability, it is unlikely also that site effects are solely responsible. It is possible that there is some contribution from a seasonal effect. However, at the Nutting site in particular, the trend has been the same through both summer (no rain) and winter (20 inches of rain). The most probable cause of the secular trend is a long-term tectonic effect on the fault. Several new installations set along two lines perpendicular to the fault should indicate whether this is the case.

For sites where seismicity is high it is difficult to isolate the effects of individual earthquakes. This is particularly evident for the Bear Valley record in Fig. 3 where seven earthquakes, ranging from $M_L = 2.5$ to $M_L = 3.1$, occur in only two months,

with epicenters quite near the instrument. New instrument sites have been located further west of the fault at Bear Valley in order to find the variation of the tilt fields with increasing distance from the fault.

5. Conclusions

A tight array of tiltmeters has been used to minitor active crustal deformation. The results indicate that regional tilting does occur before earthquakes near these instruments and that a real possibility now exists for answering many questions concerning fault tectonics and the earthquake source mechanism. The prerequisites for successful operation appear, in order of importance, to be

a) site selection,

b) mechanically and thermally stable instruments capable of at least 10^{-8} radians sensitivity,

c) stable installation,

d) a sufficiently tight array in order that some coherency is obtained between instruments,

e) installation at a distance from the fault such that minor localized tectonic behavior does not confuse the observations.

Preliminary results appear to indicate that broad scale symmetric uplift associated with earthquakes does not occur on the San Andreas fault (JOHNSTON and STUART [7], STUART and JOHNSTON [21]). Rapid non-linear tilt just prior to earthquakes, indicating the onset of catastrophic failure, has not been observed. This may be due to attenuation with distance of non-linear strain effects in the immediate source region. Tilt offsets ($>10^{-8}$ radians) associated with earthquakes occur very rarely.

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